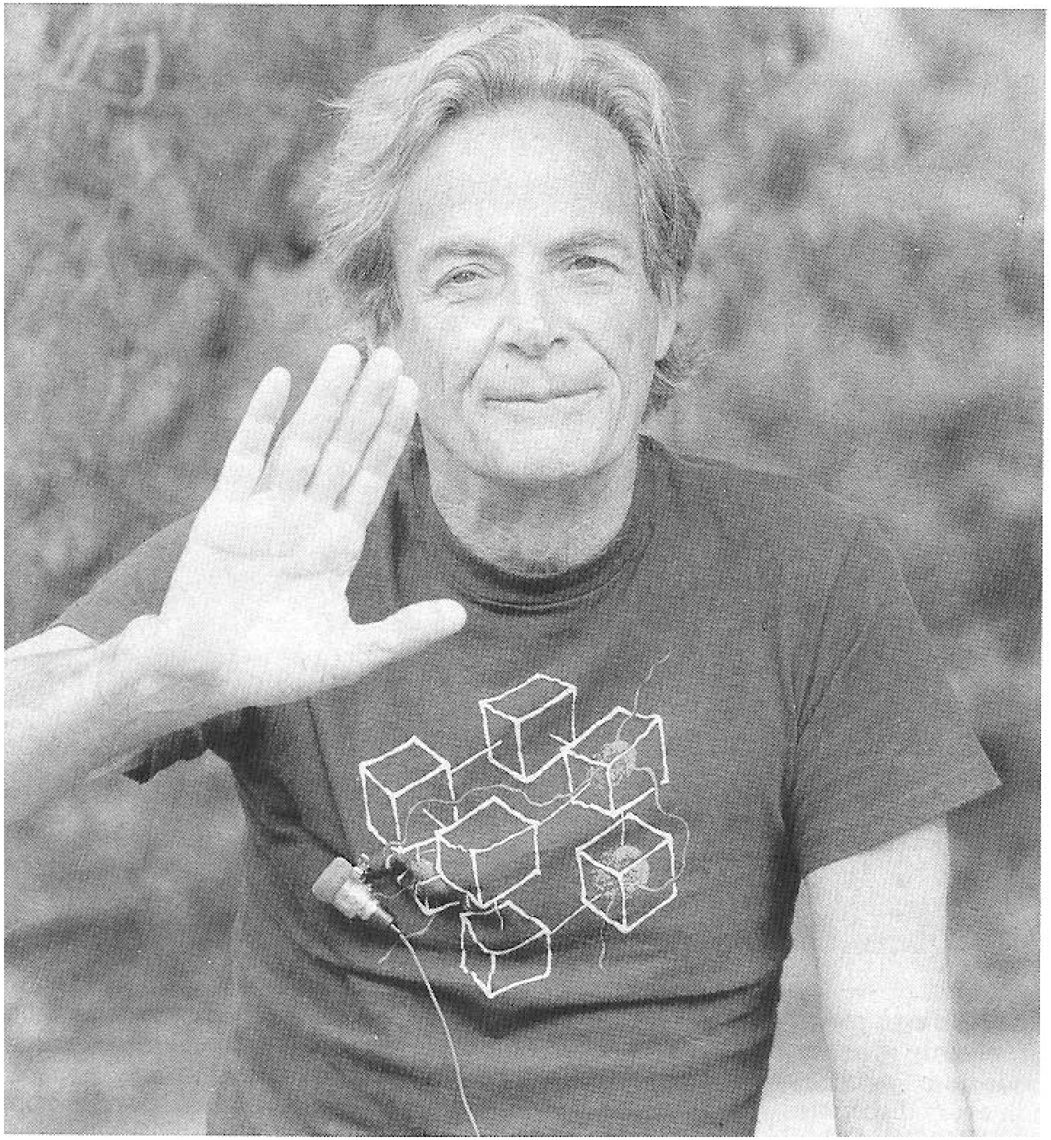
ACAT 2002

Pushpa Bhat, Fermilab

Richard Feynman at the Thinking Machines, Inc. (1983) The schematic representation of the Connection Machine that Feynman helped design, inspired the new ACAT logo.

Feynman worked out in some detail the program for computing Hopfield's neural network on the Connection Machine

Feynman also worked on cellular automata-based programs on the connection machine



Richard Feynman

Run 2 Physics at Fermilab
and
Advanced Data Analysis Methods

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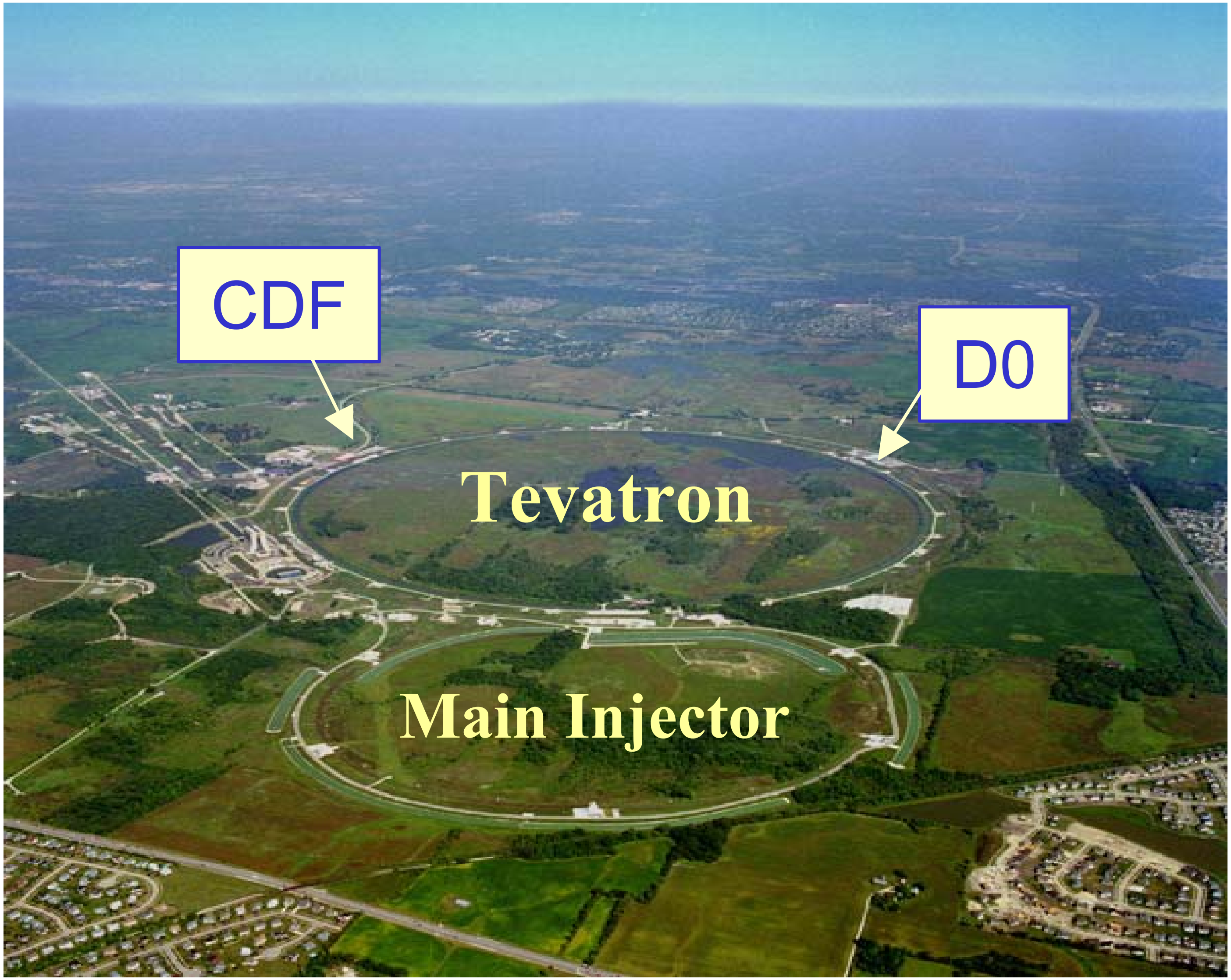
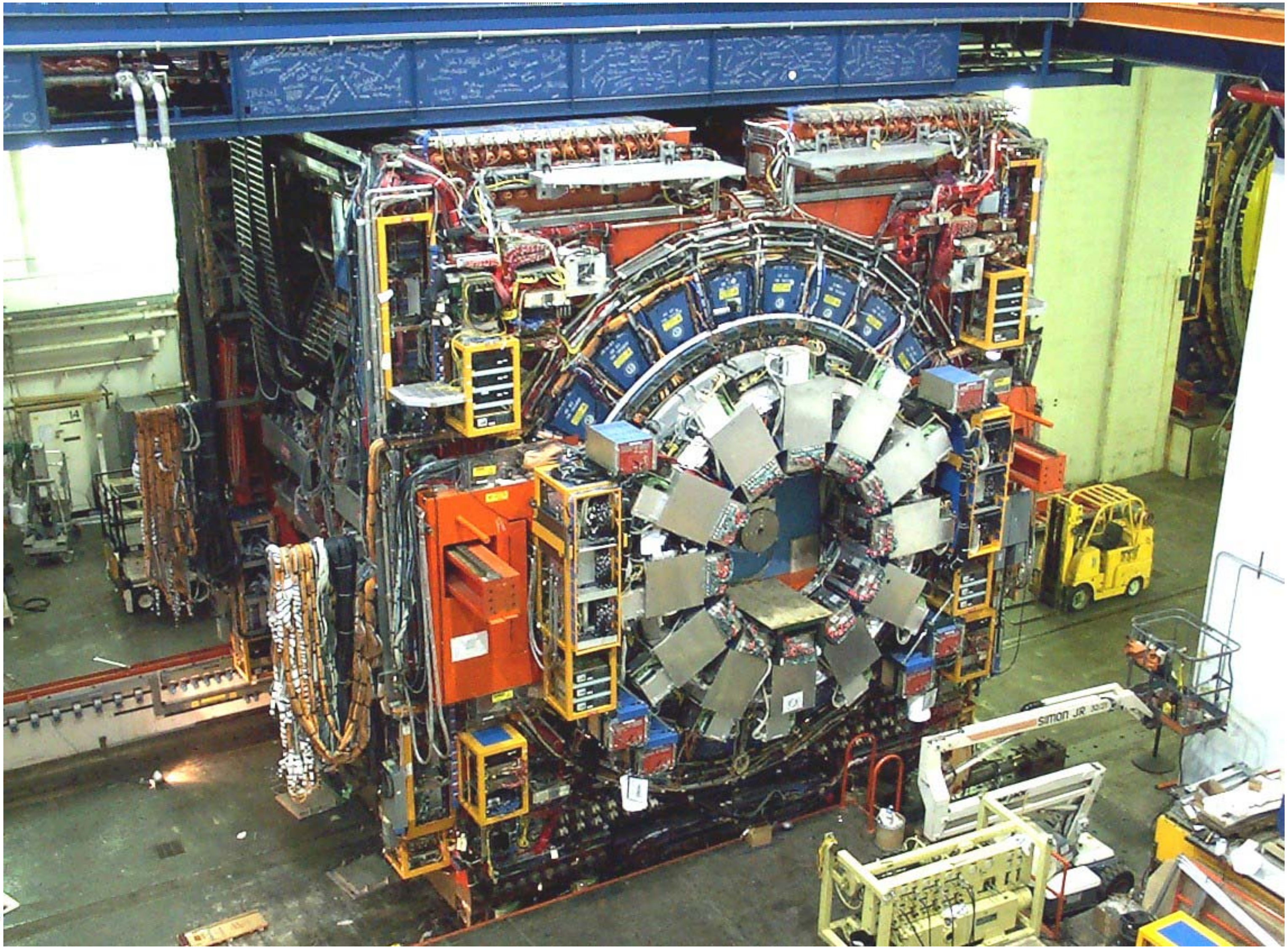
ACAT 2002 Workshop
June 24-28, 2002
Moscow, Russia

Aerial View of Fermilab Complex



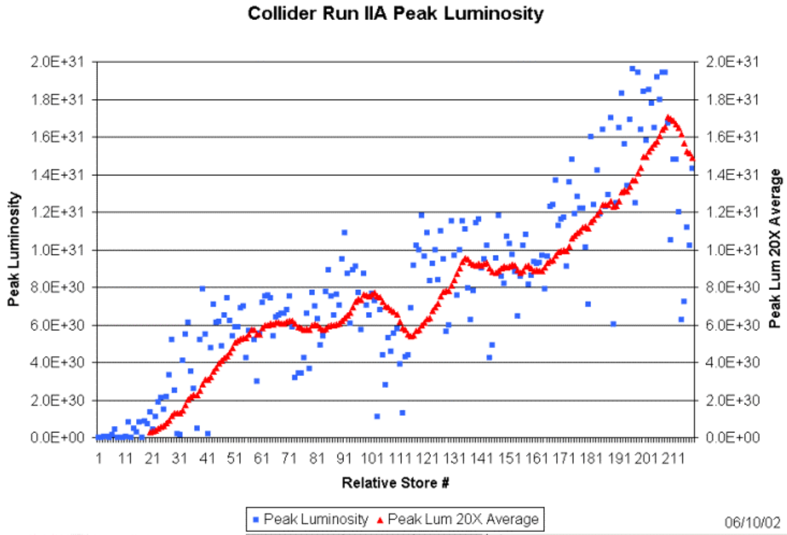
The CDF Detector

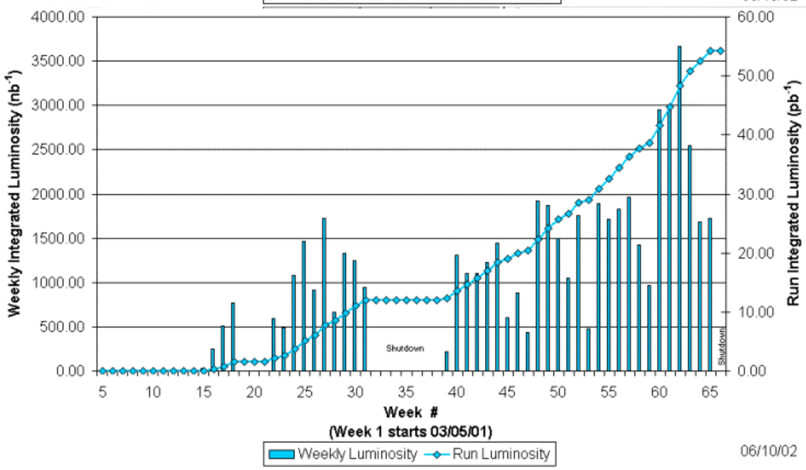


The Upgraded DØ Detector

Run 2 Status

- Several Accelerator Upgrades including new Main Injector and antiproton Recycler
- Officially started in Spring 2001
- $\sqrt{s}$ = 1.96 TeV (Run 1: 1.8 TeV)
- Commissioning & Performance Tuning
- Expected Integrated Luminosities/experiment
  - Run 2a: 2 fb^{-1}
  - Run 2b: 15 fb^{-1}
- Luminosity delivered so far: 55 pb^{-1}





Upgraded Detectors

CDF

- New Inner Tracking
- New Plug Calorimeter
- Upgraded Muon Detectors
- New Trigger and DAQ

- Large Central Tracking Volume

DØ

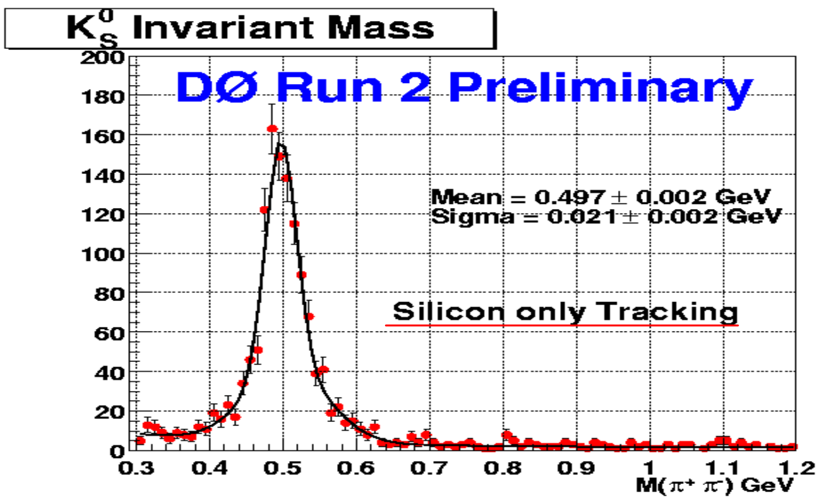
- New inner tracking with 2T superconducting solenoid
- New Preshowers
- New Trigger and DAQ

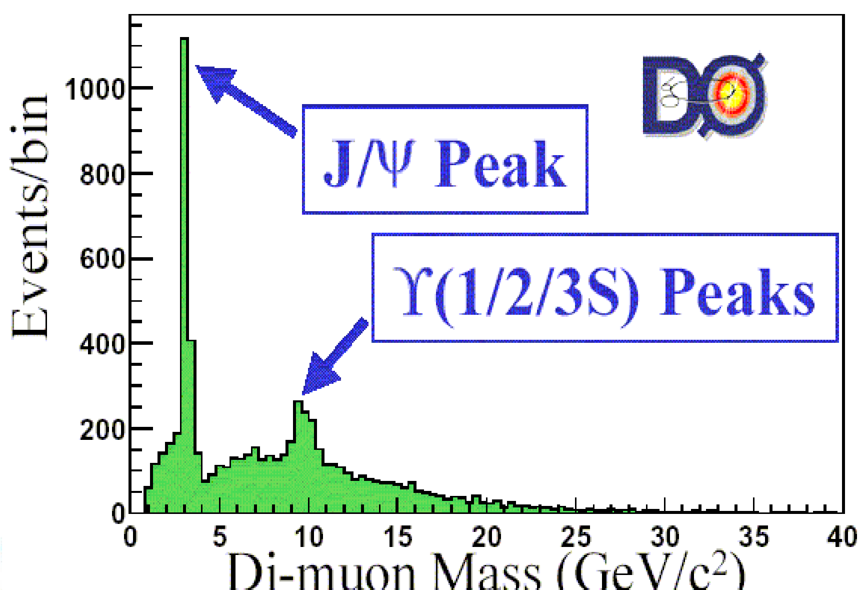
- Hermetic Compensated Uranium/LAr Calorimeter

A Rich Harvest of Physics in Run 2

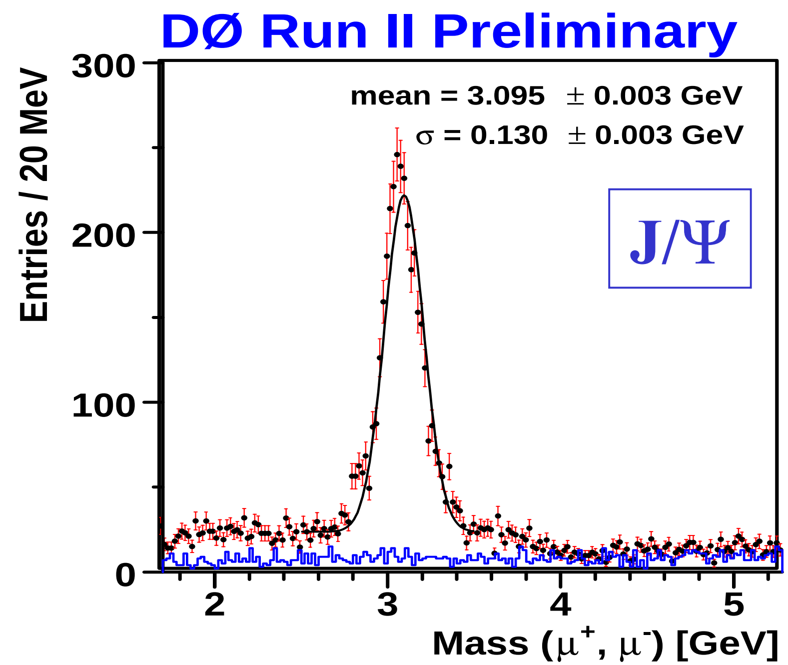
- The Standard stuff:
  - QCD Physics, Heavy Flavor, Electroweak
- Top Physics and Evidence for single top production
- Important Precision Measurements
  - W mass, top quark mass, cross sections
- Lots of interesting searches:
  - Higgs Boson
  - Supersymmetry
  - Strong Dynamics
  - Exotics: Leptoquarks, etc.
  - Extra Dimensions
- Good prospects for discovering a low mass Higgs Boson, SUSY, and possible surprises!

Standard Physics Signals



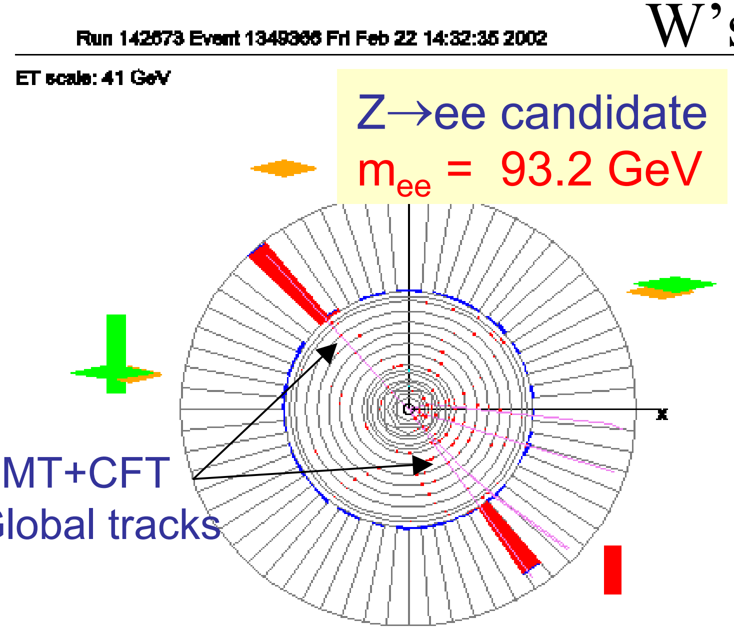


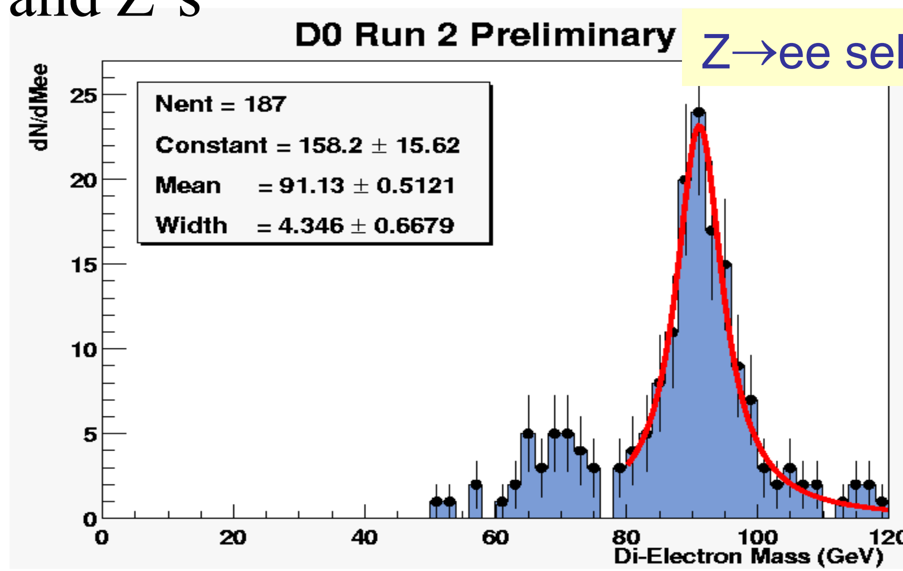
Central tracking allows significant improvement of momentum resolution for muons w.r.t. Run 1.

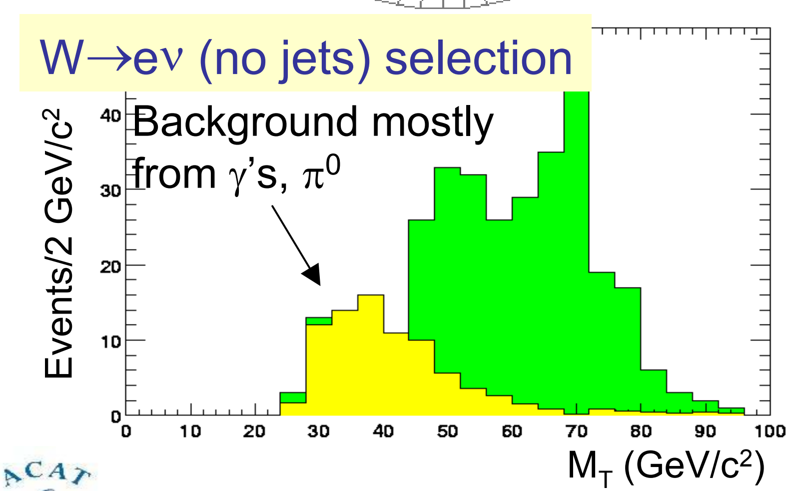


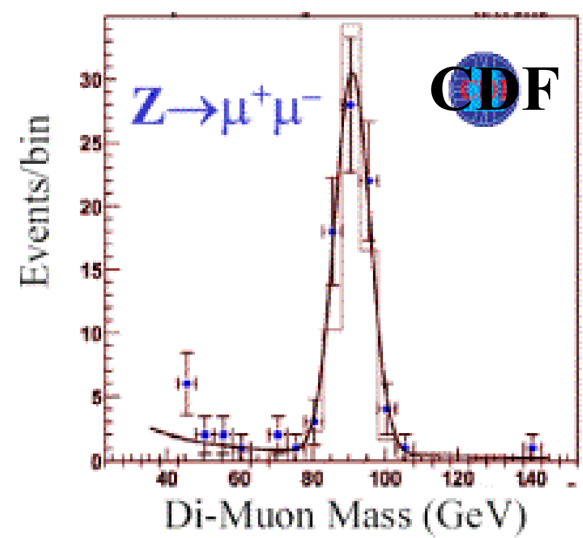
Standard Physics Signals

W's and Z's



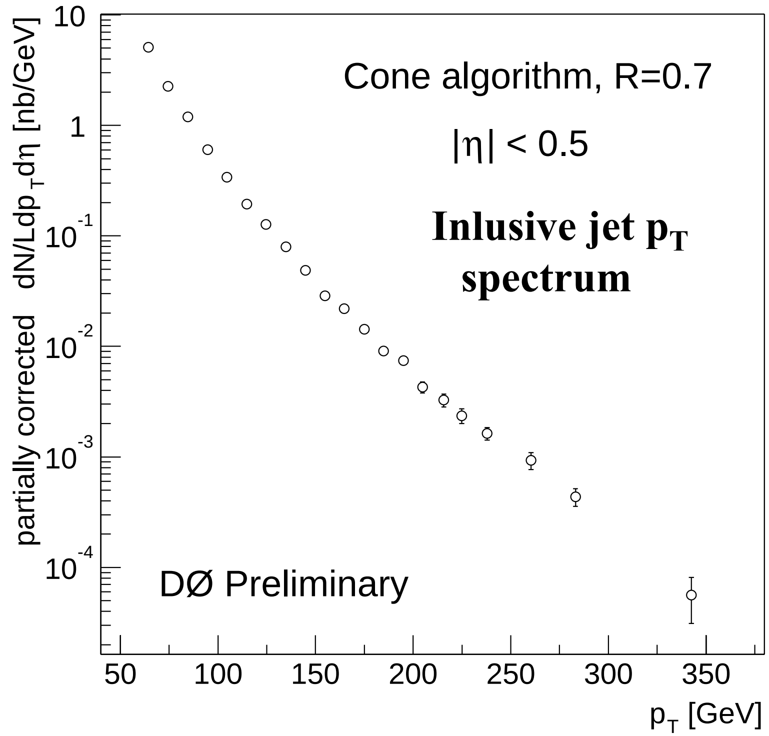


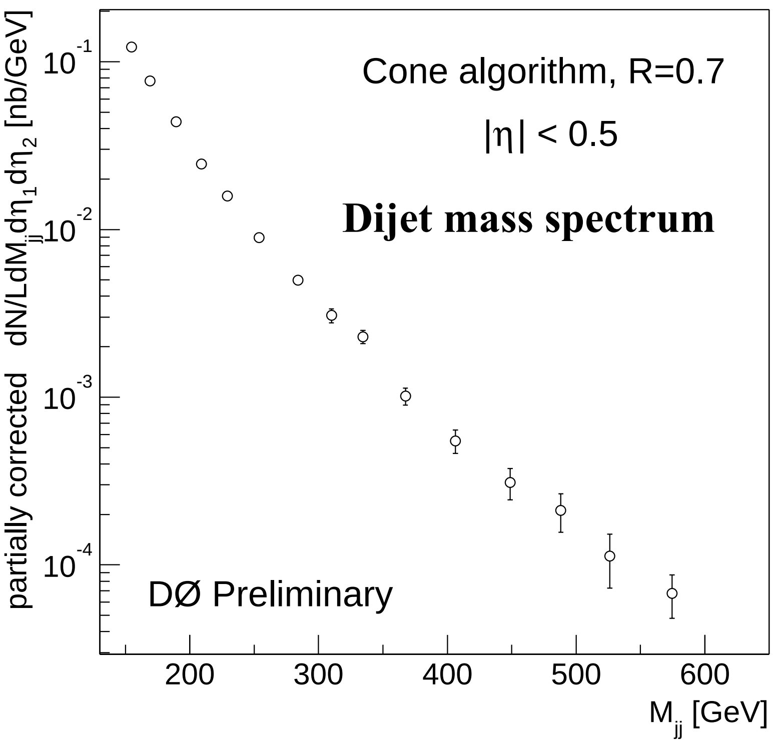




QCD Physics

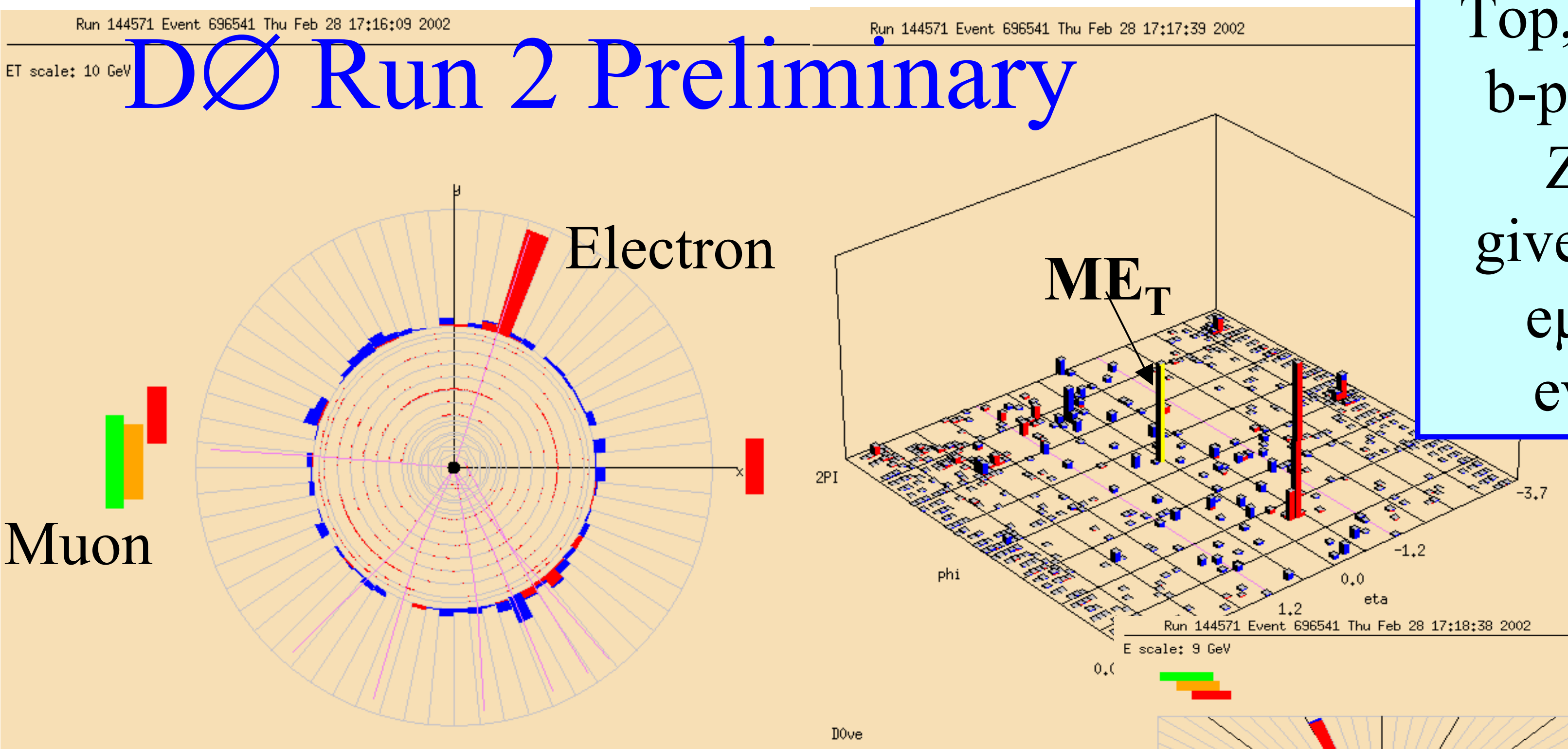
- **Integrated Luminosity ~ 1.9 pb^{-1}**



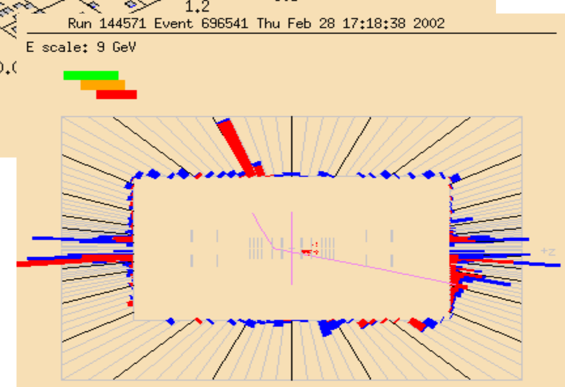


•Very preliminary corrections for jet energy

eμ Candidate Event



Top, SUSY, b-physics, Z(ττ) give rise to eμ + X events



e	μ
E_T = 13.9 GeV p_T = 9.3 GeV η = -0.425 φ = 1.251 Charge = -1	p_T (toroid) = 16.4 GeV p_T (central) = 6.3 GeV η = -0.461 φ = 2.967 Charge = +1
ME_T = 6.0 GeV	

Advanced Data Analysis Methods

- It is well recognized by now that Advanced Multivariate & Statistical Data Analysis techniques are crucial for the success of our physics program
- Best use of data i.e., maximal use of available information is necessary to achieve
  - Optimal Separation of Signal and Background
  - Optimal Measurements
  - Accurate Estimation of Errors
- The goal is to enable new discoveries, and produce results with better precision, robustness and clarity

Data Analysis Tasks

- Particle Identification
  - e-ID, τ-ID, b-ID, e/γ, q/g
- Signal/Background Event Classification
  - Signals of new physics are rare and small
- Parameter Estimation
  - t mass, H mass, track parameters, for example
- Function Approximation
  - Correction functions, tag rates, fake rates
- Data Exploration
  - Data-driven extraction of information, latent structure analysis

The Golden Rule

Keep it simple
As simple as possible
Not any simpler
- Einstein

Some Multivariate Methods

- Fisher Linear Discriminant (FLD)
- Principal Component Analysis (PCA)
- Independent Component Analysis (ICA)
- Self Organizing Map (SOM)
- Random Grid Search (RGS)
- Probability Density Estimation (PDE)
- Neural Network (NN)
- Support Vector Machine (SVM)

The Neural Network Revolution

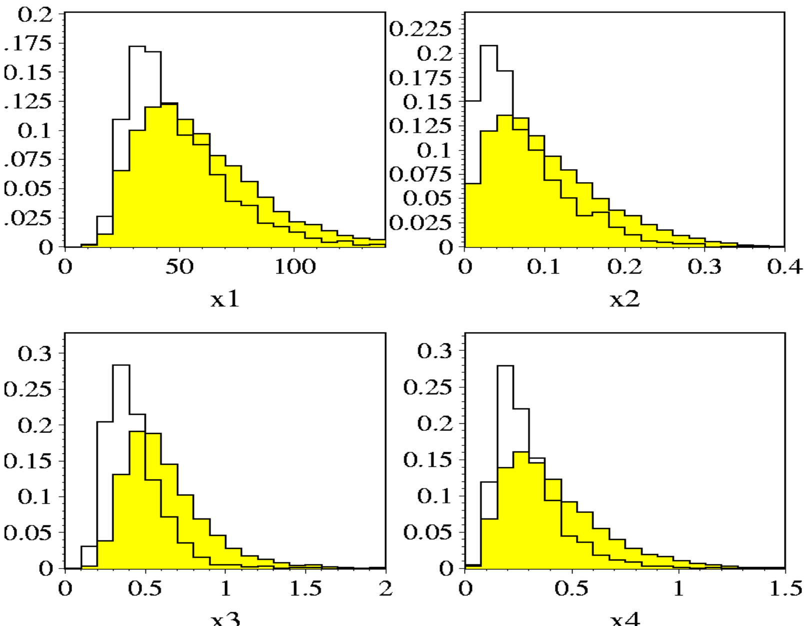
- **Key factors responsible for the sweeping success of Neural Networks:**
  - **Power**
  - **Ease of use**
  - **Successful Applications**

Examples from Run 1

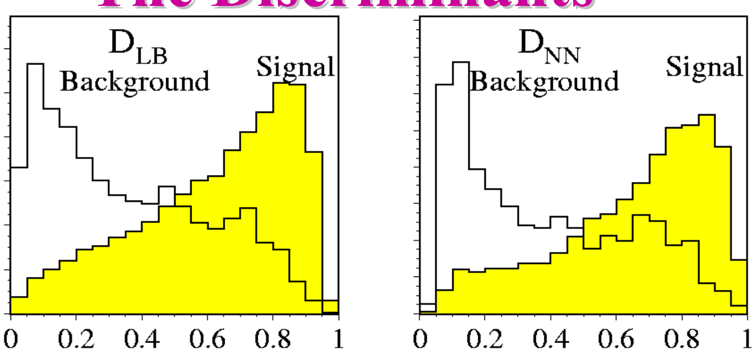
- Top Quark Discovery at DØ benefited from NN analysis: Comparisons helped arrive at optimized cuts
- Precision measurement of the top quark mass: used both NN and Bayesian analysis - the statistical uncertainty reduced by a factor of two
- Top in all-jets mode at DØ
- Limit on single top production cross section by DØ
- Top in all-jets mode and single top search by CDF
- World's best limit on 1st generation LQ mass by DØ
- And more ..

Measuring the Top Quark Mass

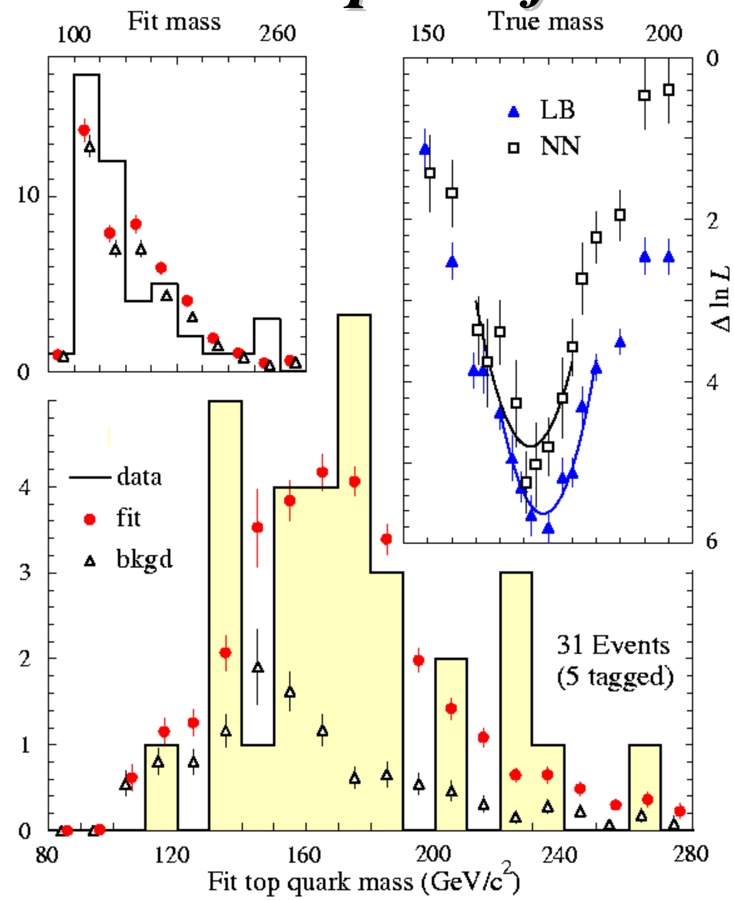
Discriminant variables



The Discriminants



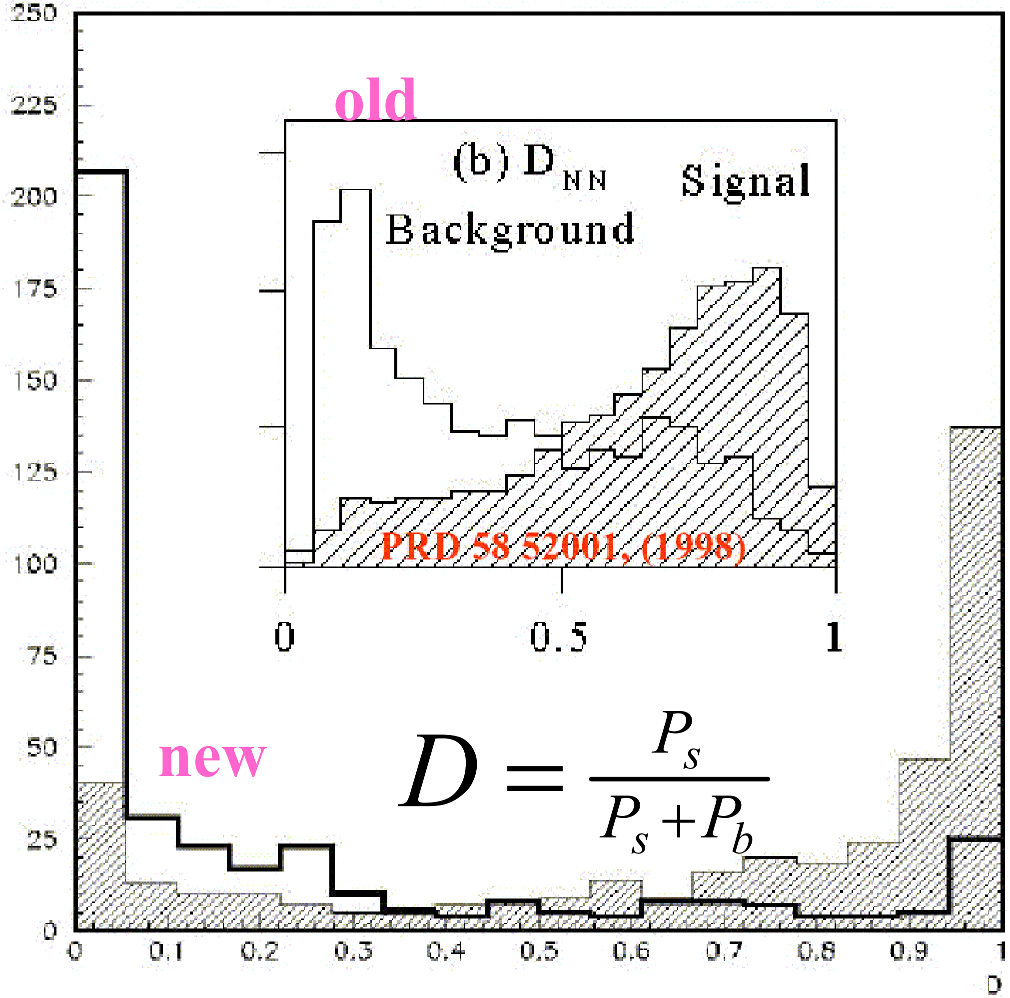
DØ Lepton+jets



$m_t = 173.3 \pm 5.6(\text{stat.}) \pm 6.2\ (\text{syst.})\ \text{GeV}/c^2$

Fit performed in 2-D: $(D_{LB/NN}, m_{fit})$

Measuring the Top Quark Mass



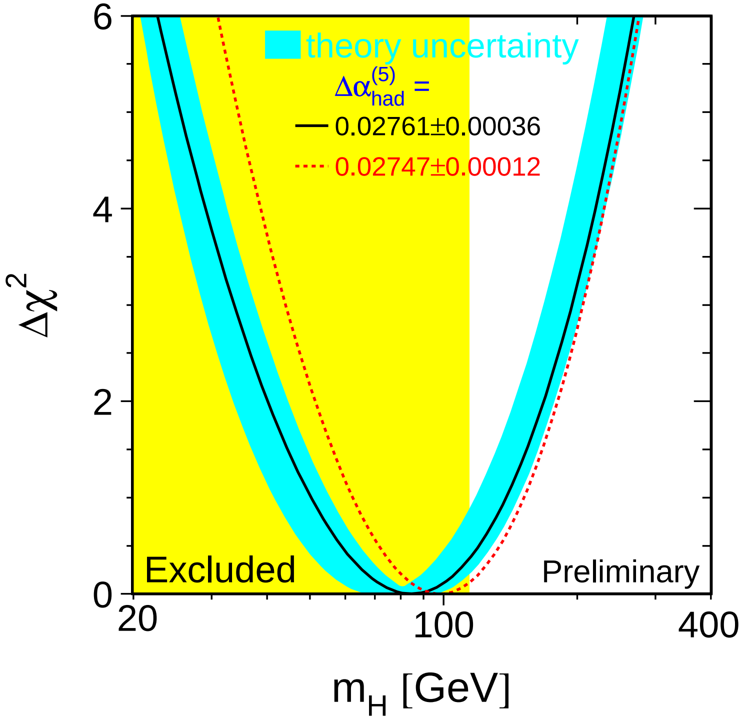
But there is more to be gained by using event by event signal probability distributions as a function of top mass and background probability, and building a likelihood for the sample, including matrix element Information.

In ensemble tests, the mass error (statistical) is a factor of 2 lower in the new method!

Top Physics in Run 2

- Advanced methods will be used in a variety of studies both at CDF and DØ
  - All hadronic decay mode
  - Tau decay modes
  - Search for single top
  - X $\rightarrow t\bar{t}$
- Recent studies at DØ show that further improvements in top mass measurement may be possible using fully probabilistic approach that exploits all features of individual events

Where is Higgs?

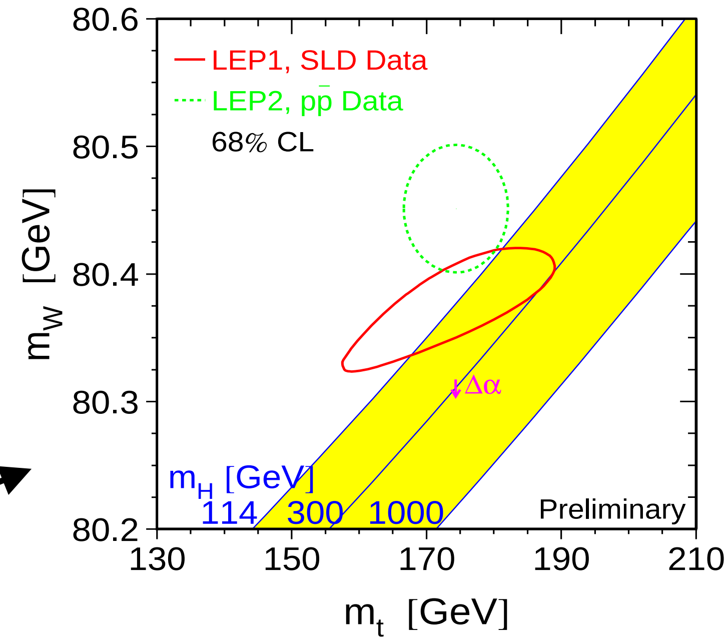


Higgs is at the heart of the EWSB pursuit

Stringent constraints on the SM Higgs mass from LEP, SLD and Tevatron data

← Precision EW measurements

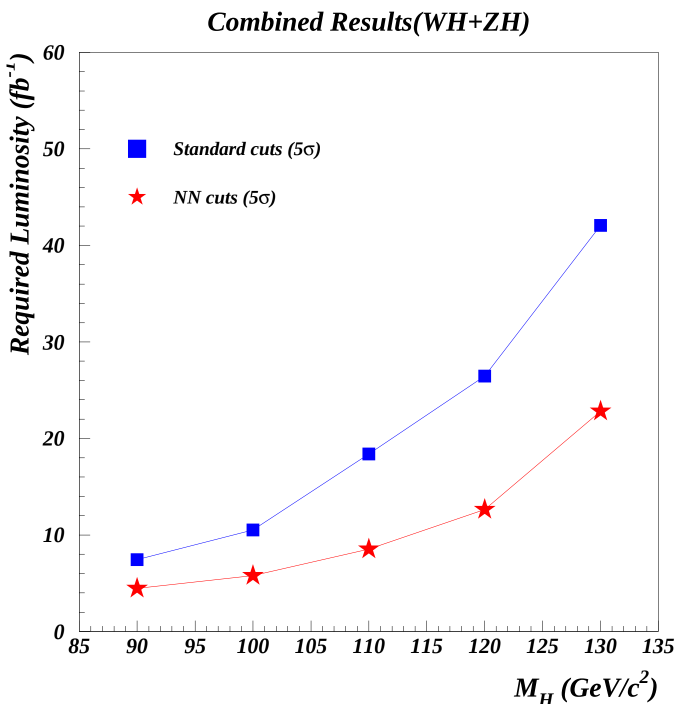
M_W, m_t measurements and correlation as predicted by EW theory for various m_H suggest a low mass SM Higgs

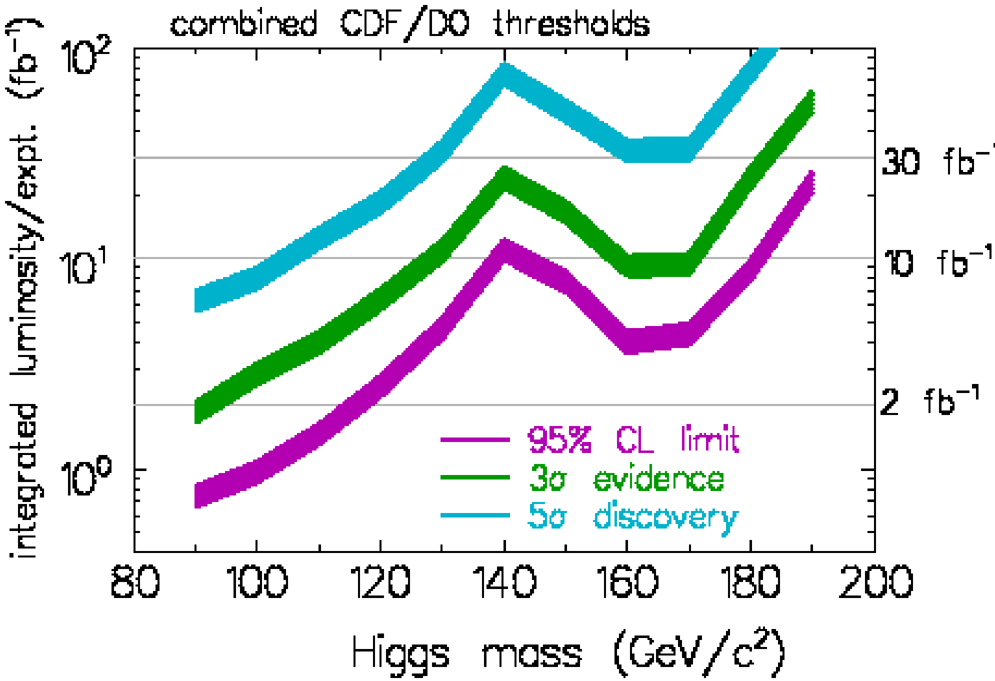


In many SUSY theories, mass of the lightest Higgs (h) < 150 GeV

Discovering the Higgs Boson

- **The challenges are daunting! But using NN provides same reach with a factor of 2 less luminosity w.r.t. conventional analysis**
- **Improved bb mass resolution & b-tag efficiency crucial**





Run II Higgs study hep-ph/0010338 (Oct-2000)
P.C.Bhat, R.Gilmartin, H.Prosper, Phys.Rev.D.62 (2000) 074022
T.Han, A.S.Turcot , and R.-J.Zhang, Phys.Rev.D59(1999)
See also Lev Dudko's talk in parallel session

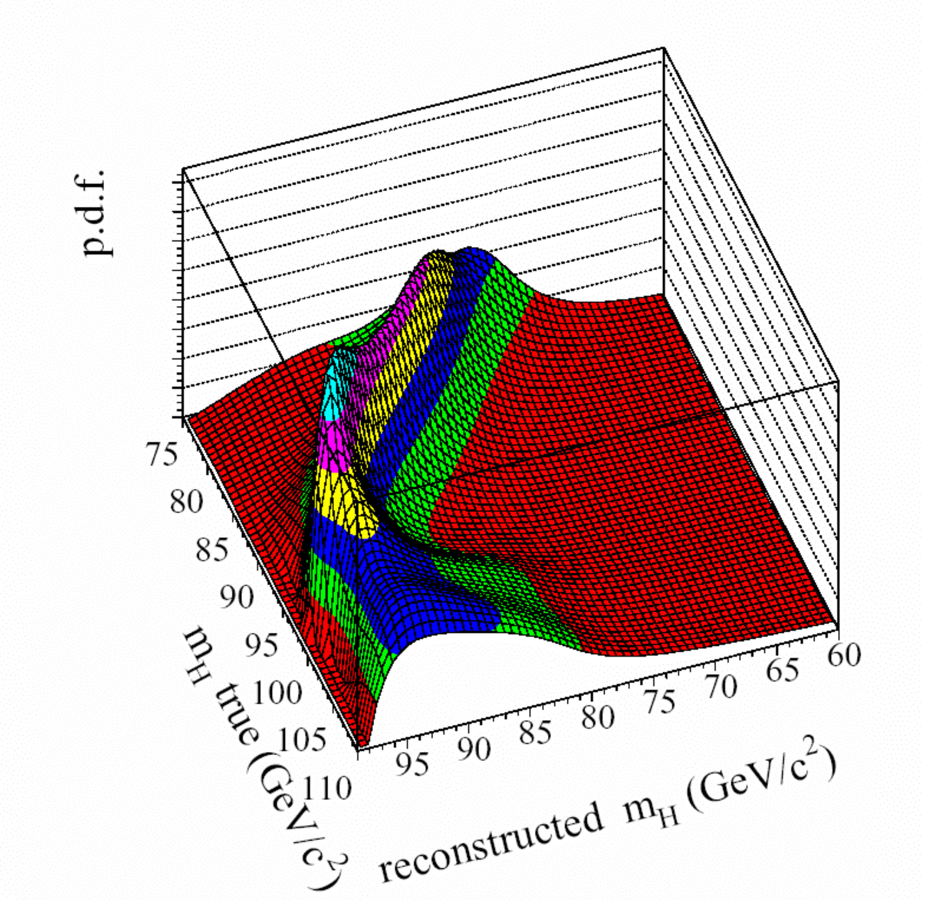
Template Fitting

- **Nice application of NN by ALEPH in the search**

$$ZH \to q\overline{q}b\overline{b}$$

- **Could be employed in top mass analysis and many other cases**

ALEPH: HZ⟶q$\bar{q}$bb Search



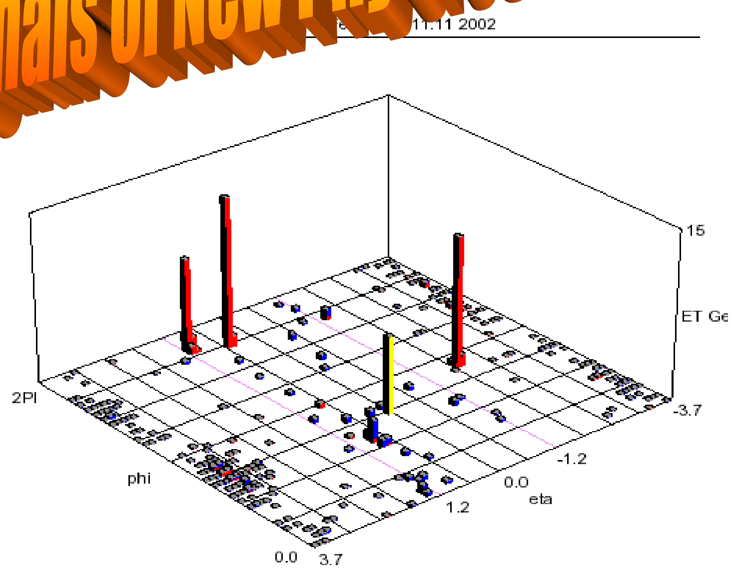
Supersymmetry and Beyond

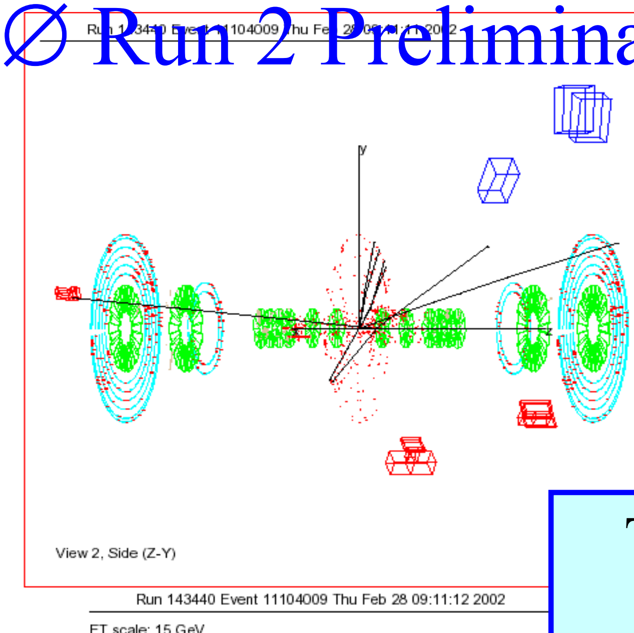
- The trilepton channels may be clean modes but jetty SUSY/technicolor channels certainly will benefit from multivariate methods
- Run 1 searches for SUSY in the e+jets +MET channel and Technirho at DØ use NN
- Big help in tau channels
- Search for Extra Dimensions (no more fiction!) benefits from tight control of fake leptons/ photons (good ID and fake rate estimation)

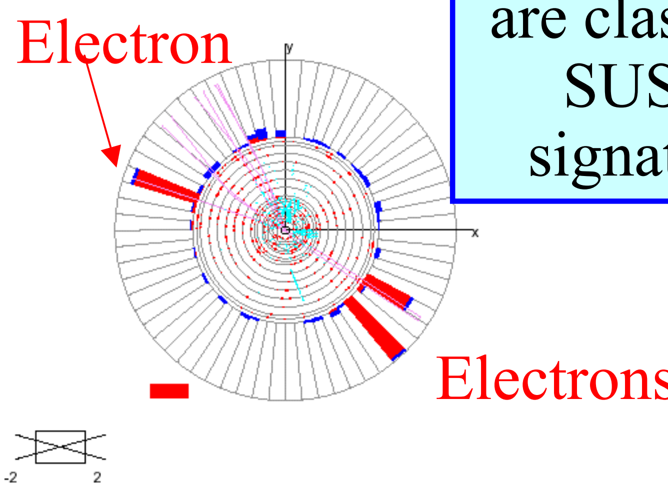
eee Candidate Event

Signals of New Physics?

DØ Run 2 Preliminary





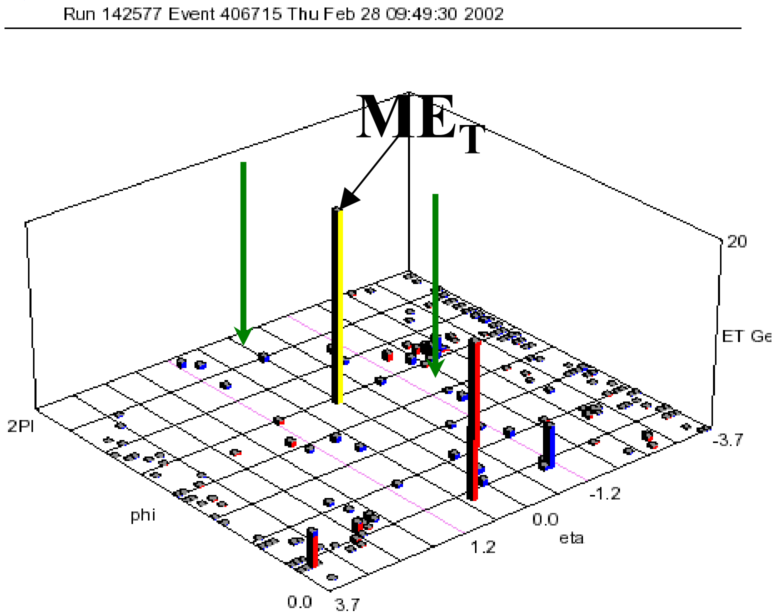


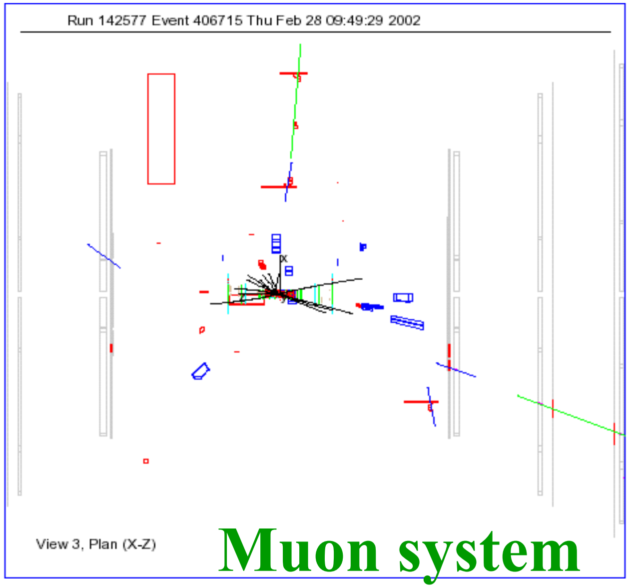
Trilepton events are classical SUSY signature

e1	e2	e3
E_T = 17.9 GeV p_T = 0.52 GeV η = 0.43 φ = 5.42 Charge = +1	E_T = 13.9 GeV p_T = 10.9 GeV η = -1.94 φ = 2.80 Charge = +1	E_T = 13.2 GeV p_T = 15.1 GeV η = 1.06 φ = 5.72 Charge = -1
m_{e1e2} = 55.7	m_{e1e3} = 10.8	m_{e2e3} = 63.5
m_{e1e2e3} = 85.2 GeV/c^2	ME_T = 10.7 GeV	

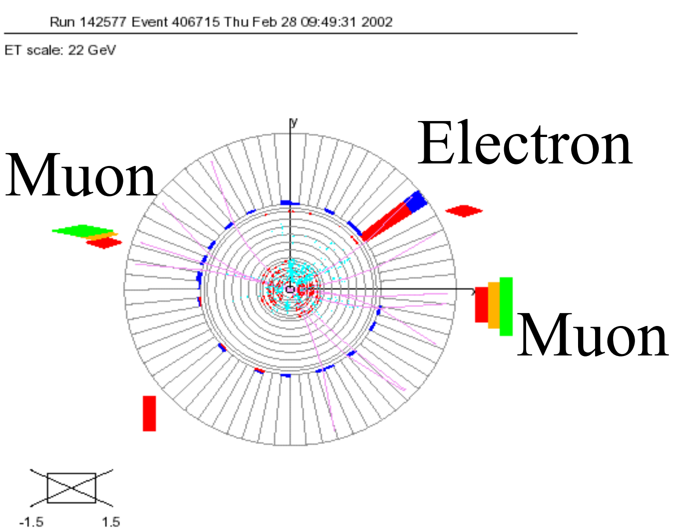
eμμ Candidate Event

DØ Run 2 Preliminary





e	μ1	μ2
E_T = 19.2 GeV η = 0.40 φ = 0.63 No track match	p_T = 28.2 GeV η = -0.10 φ = 6.20 Charge = -1	p_T = 9.82 GeV η = -1.48 φ = 2.88 Charge = 1
	$m_{\mu\mu}$ = 41.5 GeV/c^2	
ME_T =31.8 GeV		



Multivariate Analysis Issues

- Dimensionality Reduction
  - Choosing Variables optimally without losing information
- Choosing the right method for the problem
- Controlling Model Complexity
- Testing Convergence
- Validation
  - Given a limited sample what is the best way?
- Computational Efficiency

More Issues

Apart from the usual stuff,

- Quantifying correctness of modeling or goodness of learning (fit)
- Checking the robustness of results
- Abstracting the response function or the mapping function from Monte Carlo
  - Inverse Monte Carlo (?)

Multivariate Methods and Bayesian Statistics

- Both Ancient Concepts; A lot of new approaches, algorithms and applications
- Adaptive learning and Stochastic optimization revolutionized the landscape for multivariate analysis
- Some hard problems can’t be solved without Bayesian thinking!
- New Kids on the Block in HEP; Concerns
- 1990’s: Why NN or Why Bayesian?

  Now: Why NOT?

Exploring Models: *Bayesian Approach*

- Enables straight-forward and meaningful model comparisons.
- Allows treatment of all uncertainties in a consistent manner.
- Provides probabilistic information on each parameter of a model (SUSY, for example) via marginalization over other parameters
- Mathematically linked to adaptive algorithms such as Neural Networks (NN)
- Hybrid methods involving multivariate probability density estimation and Bayesian treatment can be very powerful

Summary

- Run 2 at Fermilab is well underway; CDF and DØ will record unprecedented amounts of data in the coming years: 2 fb^{-1} in Run 2a, > 15 fb^{-1} in Run 2b
- Use of advanced "optimal" analysis techniques will be crucial to achieve the physics goals
- Multivariate methods, particularly Neural Network techniques, have already made impact on discoveries and precision measurements and will be the methods of choice in future analyses
- Hybrid methods combining "intelligent" algorithms and probabilistic approach will be the wave of the future
- We hope to unravel some of nature's mysteries!